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Sunglasses, Traffic Signals, and Color Vision Deficiencies

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ABSTRACT

Purpose. To determine a) the effect of different sunglass tint colorations on traffic signal detection and recognition for color normal and color deficient observers, and b) the adequacy of coloration requirements in current sunglass standards.

Method: Twenty color-normals and 49 color-deficient males performed a tracking task while wearing sunglasses of different colorations (clear, gray, green, yellow-green, yellow-brown, red-brown). At random intervals simulated traffic light signals were presented against a white background at 5° to the right or left and observers were instructed to identify signal color (red/yellow/green) by pressing a response button as quickly as possible; response times and response errors were recorded.

Results: Signal color and sunglass tint had significant effects on response times and error rates ($p < 0.05$), with significant between-color group differences and interaction effects. *Response times* for color deficient people were considerably slower than color normals for both red and yellow signals for all sunglass tints, but for green signals they were only noticeably slower with the green and yellow-green lenses. For most of the color deficient groups, there were *recognition errors* for yellow signals combined with the yellow-green and green tints. In addition, deuteranopes had problems for red signals combined with red-brown and yellow-brown tints, and protanopes had problems for green signals combined with the green tint and for red signals combined with the red-brown tint.

Conclusion: Many sunglass tints currently permitted for drivers and riders cause a measurable decrement in the ability of color deficient observers to detect and recognize traffic signals. In general, combinations of signals and sunglasses of similar colors are of particular concern. This is *prima facie* evidence of a risk in the use of these tints for driving and cautions against the relaxation of coloration limits in sunglasses beyond those represented in the study.

People with deficient color vision have problems detecting and recognising road traffic signals. The problems involved are increases in reaction time, relative to those of people with normal color vision, and incorrect recognition[1-7]. These problems increase with severity eg dichromats compared with anomalous trichromats. Nathan et al.[4] found that protans performed worse than deutans, but Atchison et al.[1] found the opposite effect, with the reasons for the difference explained by Cole[8]. There is also some evidence that protans have higher road accident rates than color normals[7,9-11].

It has long been recognised that colored sunglasses might impair recognition of signal lights, especially for drivers with defective color vision. Based on some experimental measurements in the literature, but mainly on his own theoretical determinations, Clark argued that sunglass coloration should not depart very much from neutral, and he proposed that this should be determined by signal factors.[12,13] He recommended a red signal visibility factor (R) and a violet coloration factor (V) which are the ratios of the amounts of red and violet light, respectively, transmitted through a lens relative to the luminous transmittance through the lens. The former should be within certain limits and the latter should have a minimum value so that the already degraded color perception of color deficients across the visual spectrum should not be worsened by lenses that transmit little or no violet light.

Clark's ideas were taken up in the first[14] and subsequent Australian sunglass standards (Table 1). At the time that this study was conducted, the then Australian sunglass standard AS 1067-1990[15] argued:

> *Lenses with an R less than 1.0 can decrease the visibility and increase the reaction time for red signals, and colour identification can also be adversely affected, especially for a person with defective colour vision. Lenses with R greater than 1.0 can adversely affect the brightness cues used by colour defectives in identifying red. Lenses which do not transmit sufficient violet light can seriously degrade colour perception, especially for colour defectives.*

In AS 1067-1990 "general purpose" sunglasses (between 8% and 50% luminous transmittance) were required to have R and Vs greater than 0.70 and 0.3, respectively. If they had R factors greater than 1.40, they were to be labeled: *"Not suitable for persons with defective colour vision"* or *"Not suitable for persons with defective colour vision. These lenses will further distort their colour perception*." "Specific purpose sunglasses" had stricter ultraviolet absorption requirements than general purpose sunglasses and were classified as either type (a) or type (b). Type (a) had stricter R requirements than general purpose sunglasses ($0.85 \leq R \leq 1.15$), and a stricter V of ≥ 0.5. Type (b) has no coloration limits, but had to be labeled: *"Not suitable for driving"* or *"Because they distort colour perception, these lenses are inappropriate for driving"* or, where the lenses did not meet the minimum coloration limits for the general purpose sunglasses, they had to be labelled *"Not suitable for persons with defective colour vision"* or *"Not suitable for persons with defective colour vision. These lenses will further distort their colour perception"* if the lenses had R factors greater than 1.40.

Sunglass standards around the world now impose coloration requirements on sunglasses to limit color distortions, especially those that might impede recognition of road traffic signals. The United States, European and current Australian standards express their signal visibility or coloration factors differently from those of AS 1067:1990 (Table 1).[15-20] The current US standard ANSI Z80.3 2008[16] has minimum sunglass transmittances for daylight (D65 light source) and red signal lights of 8%, and minimum transmittances for green and yellow signal lights of 6%. These are absolute transmittances, whereas the other standards allow for adaptation in the visual system by specifying relative transmittances. The US standard also specifies maximum color shift limits for these lights. It requires that the minimum transmittance across the wavelength range of 475 nm to 650 should be at least 20% of the luminous transmittance. The European Standard EN 1836:2005[17] defines "relative visual attenuation quotients" for sunglass lenses for each of blue, green, yellow and red signal colors, each of which has different compliance values. It also requires that the minimum transmittance across the wavelength range of 500 nm to 650 should be at least 20% of the luminous transmittance. The US standard is considerably more lenient than the European standard with regard to coloration, but many sunglasses sold in that country still fail its coloration limits.[21] The

European and US Standards are substantially more lenient than AS 1067:1990 in the blue end of the spectrum.

The current Australian and New Zealand Standard on sunglasses AS/NZS 1067:2003[18] is technically equivalent to the European Standard[17] but the compliance requirements vary in some measures. AS/NZ1067:2003 has a higher compliance value than EN 1836 for the blue signal color (0.7 compared with 0.4) and the range across which the minimum spectral transmittance should be compared with the luminous transmittance is extended to 450 nm (Table 1).

The research reported in this paper forms part of a larger laboratory study investigating the effect of color vision deficiency on signal detection response times and on the accuracy of recognition of the signals. The aims of this component of the study were a) to assess the extent to which sunglasses of a range of colorations impede the detection and recognition of traffic signal lights, and b) to establish whether Australian and other standards are adequate in specifying sunglass coloration limits.

Method

Sunglasses were developed by dyeing plano plastic CR39 lenses to achieve the appropriate tint characteristics required for the study. Each pair of lenses was measured spectrophotometrically (Varian Cary 5000 UV-VIS-NIR spectro-photometer) at the Optics and Radiometry Laboratory (ORLAB) of the University of New South Wales. An untinted pair (Clear) and a neutral density pair (Gray) acted as controls. The lenses were fitted into spectacle frames that required minor adjustment to fit each observer's head comfortably. Figure 1 shows their spectral transmittances. Table 2 lists the tints, together with the ways in which their coloration factors fall outside the limits for the General Purpose sunglass category of AS 1067:1990. The tints had luminous transmittances of 21% to 31%. Three pairs of lenses (Yellow-Green, Yellow-Brown and Red-Brown) had R factors greater than 1.4 (high), one pair (Green) had an R factor less than 0.70 (low), and three pairs had V factors less than 0.3 (Green, Yellow-Green and Yellow-Brown). The tints lie within the spread of colors typically seen in the sunglasses that have been tested by ORLAB in recent years (about 2000 pairs a year).

Table 2 indicates also where the tints were outside the specified limits for AS/NZS 1067:2003, EN 1836:2005 and ANSI Z80.3:2008. The Green tint failed each standard on one or more criteria, the Yellow-Green tint failed the AS/NZS 1067:2003 and ANSI Z80.3:2008 standards, and the Yellow-Brown and Red-Brown lenses passed all three standards.

Observer and experimental information have been reported in detail previously[1] Observers were 69 young, healthy (16-35 years) males, consisting of 20 color normals, 15 deuteranomals, 10 deuteranopes, 15 protanomals and 9 protanopes. Selection criteria are given in Table 3. All observers had binocular visual acuity of 6/6 or better, with 11 observers wearing their (untinted) ophthalmic corrections behind the sunglass tints to achieve this visual acuity.

Observers viewed a fixation target in the centre of a computer monitor at a 4 m working distance (Figure 2). Simulated single aspect traffic signals were displayed for a maximum of 5 seconds at 5 degrees either side of fixation and observers were instructed to identify the color as quickly as possible.

Signal size was equivalent to that of 200 mm traffic signal lantern at 100 m distance (2 mrad), which is the standard Australian practice.[22,23] Signals were created with 20W 12V tungsten halogen globes and filters to provide the appropriate traffic signal chromaticity co-ordinates. Intensity was controlled using neutral density filters. The chromaticity co-ordinates of the signals, from spectral radiance measurements made with a Topcon SR-3 telespectroradiometer, are represented in Figure 3(a-c) by open circles. Also shown are the color requirements of the signals. The international standard on traffic signals[24] references the IS0/CIE S 004 standard on colors of signal lights[25]. The red signals lie within the class A1 limits which are specified “when persons with defective color vision are included in the user group”. The yellow signals lie within the permitted limits for yellow (there are no classes) and the green signals lie within the Class A requirements which are for the same application as Class A1 red. In other words, the colors were, in the context of CIE S 004, optimised for use by people with defective color vision. The chromaticity coordinates of the signals viewed through the tinted lenses were calculated using the CIE 2° standard observed and are represented by the other symbols in Figure 3 (a-c).

We presented signals of low intensity - 0.32 cd for red and green and 0.96 cd for yellow and high intensity - 0.64 cd for red and green and 1.92 cd for yellow which are the 4 m equivalent of the 200 mm traffic signal at 100 m complying with the maximum and minimum AS/NZS2144 requirements[23]. The signals were surrounded by black backboards in scale with the backgrounds around normal traffic lights[22,23]. Around the computer monitor and the black backboards was a white matt board illuminated by two fluorescent light tubes to provide 300 cd/m^2 luminance.

The experiment was divided into three sections – button reaction time, practice and the experiment proper. The reaction times for the first section were used to adjust response times for data analysis. The first two sections are described in our previous paper. In the experiment proper, we simulated driving using a divided attention task. The fixation target was a 1.5cm diameter circle which moved in straight lines at random speed and direction on the computer monitor. The observers were asked to place the fixation target inside a 1.5 x 2 cm rectangle by moving the computer mouse. They received feedback by the circle changing into a cross when they were successful. At random intervals of between 6 and 12 seconds, either the left or the right light was turned on. The observer abandoned the tracking task, identified the color as quickly as possible and indicated this by pressing one of three buttons on the computer mouse: left button for red, middle button for yellow, and right button for green. Failure to respond within 3 seconds was regarded as a detection failure. After the response (or after 5 seconds if no response) the next sequence began.

The observers informed the experimenter immediately if they had made a mistake in responding to a light. This was later correlated with the computer's record of responses and these "mistakes" were not used in analysis (mean ± SD = 2 ± 1%). Observers were not given feedback about which lights were correctly or incorrectly identified.

Target presentation and response recording were under computer control. Each run consisted of 12 presentations, with 1 presentation on each side of low and high luminance red, yellow and green lights. These presentations were randomized within each run. There were 4 runs per signal color, so each color was presented 16 times for each sunglass tint. At the completion of a set of runs, the next sunglass was selected. The order of sunglass wear was randomized between observers, using an incomplete Latin square design.

Repeated measures ANOVA were conducted for both response time and response accuracy with two within group factors (lens tint (6 levels) and signal color (3 levels)) and one between subjects group factor (normals, deuteranomals, deuteranopes, protanomals and protanopes). In the previous paper[1] we used the term “mean adjusted response time” to allow for the button reaction time, but here we simply use the term “response time”. Sphericity assumptions for some of the analyses were violated. Analyses are therefore reported as significant only if they were also significant with adjustment for sphericity via the Greenhouse-Geisser epsilon. Given the large number of conditions in the experiment, it was not considered valid to conduct all possible follow-up comparisons, so visual inspection was used as the basis for the interpretation of any significant interactions.

RESULTS

Response times

There were significant main effects of signal color ($F_{2,128} = 83.72$; $p < .001$) and lens tint ($F_{5,320} = 33.35$; $p < .001$) on response times and the group effect was also significant ($F_{4,64} = 14.18$; $p < .001$), where the deuteranopes had significantly longer response times than all the other groups except for the protanopes. Figure 4 shows response times for the different color vision groups, collapsed across all signals, for each sunglass tint. It clearly shows that the response times for all color deficient groups were longer than those of the color normals for the Clear and Gray lenses.

There were also significant two-way interactions between signal color and group ($F_{8,128} = 8.15$; $p < .001$), lens color and group ($F_{20,320} = 3.66$; $p < .001$), as well as a three-way interaction between signal color, lens color and group ($F_{40,640} = 2.96$; $p < .001$). As seen in Figure 4, the Green and Yellow-Green lenses exacerbated the increase in response times for all of the color deficient groups relative to the color normal group.

Given the significant three way interaction, the data were broken down and analysed for each of the five participant groups. Results for the normal group are shown in Figure 5a. There was a significant main effect of signal color ($F_{2,38} = 6.67$; $p=0.003$) but not lens tint ($F_{5,15} = 0.15$; $p = 0.98$) on response times. There was also a significant interaction effect between signal color and lens tint ($F_{10,190} = 5.97$; $p = 0.045$), where response times were increased when viewing the Y signal through the Yellow-Green lens relative to the other lens tints, and responses times were decreased when viewing the R signal through the Yellow-Green lens.

Results for the deuteranomals are shown in Figure 5b. The response times were significantly affected by signal color ($F_{2,28} = 12.0$; $p<0.001$) and lens tint ($F_{5,70} = 10.08$; $p <0\ .001$), and there was also a significant interaction between signal color and lens tint ($F_{10,140} = 11.61$; $p <0\ .001$). Examining the two-way interaction (Figure 5b) it is evident that response times were slower to the G signal when viewed through the Green lens and to the Y signal when viewed through the Yellow-Green lens compared with the other lens tints.

Results for the deuteranopes are shown in Figure 5c. The response times were significantly affected by signal color ($F_{2,18} = 21.55$; $p < .001$) and lens tint ($F_{5,45} = 3.65$; $p = 0.007$). The observers responded slower to the R signal, across all lenses, than to either Y or G signals, and they responded slower to the Y than to the G signal. The differences were considerable at 59% (R versus G) and 47% (Y versus G). There was also a significant two-way interaction between signal color and sunglass lens tint ($F_{10,90} = 3.01$, $p = 0.003$), where response times to the G signal were longer when viewed through the Green and Yellow-Green lenses compared with the other sunglass lens tints (Figure 5c).

Results for the protanomals are shown in Figure 5d. The response times were significantly affected by signal color ($F_{2,28} = 28.89$; $p < 0.001$) and lens tint ($F_{5,70} = 9.33$; $p < 0.001$), and there was also a significant interaction between signal color and lens tint ($F_{10,140} = 7.12$; $p < 0.001$). The significant interaction effect reflects the increase in response times to the G signal viewed through the Green lens and to the R signal viewed through the Red-Brown lens.

Results for the protanopes are shown in Figure 5e. The response times were significantly affected by signal color ($F_{2,16} = 25.95$; $p < 0.001$) and lens tint ($F_{5,40} = 11.32$; $p < 0.001$) and there was also a significant two-way interaction ($F_{10,80} = 7.0$; $p < 0.001$). This interaction effect reflects the increase in response times to the G and Y signals for the Green and Yellow-Green lenses; interestingly, the effects of signal color were greatest for the Red-Brown lens, where responses were clearly slower to the R and Y signals compared to the G signal.

From considering Figures 5a-e it is clear that the response times of the color normals were less affected by either signal color or sunglass tint than were the color deficient groups. Response times for the color deficient groups were considerably slower than the color normals for both R and Y signals at all sunglass colors, but for the G signals they were only noticeably slower with the Green and Yellow-Green lenses.

Errors

There were significant main effects of signal color ($F_{2,128} = 42.41$; $p < 0.001$), and sunglass tint ($F_{5,320} = 9.58$; $p < 0.001$) on error rates. The group effect was also significant ($F_{4,64} = 37.33$; $p < 0.001$), with the deuteranopes making significantly more errors than any other group, as shown in Figure 6 which represents error rate as a function of sunglass tint and group collapsed across all signal colors. There were also significant two-way interactions between signal color and group ($F_{8,128} = 12.99$; $p < 0.001$), between lens color and group ($F_{20,320} = 1.88$; $p = 0.013$) and a three-way interaction between signal color, lens color and group ($F_{40,640} = 2.77$; $p < 0.001$). Given the 3-way significant interaction effect, the data were broken down and analysed for each of the five participant groups.

Results for the normal group are shown in Fig. 7a. There were no significant effects of signal color ($F_{2,38} = 2.38$; $p = 0.106$) or sunglass lens tint ($F_{5,95} = 2.14$; $p = 0.068$) on error rates, but there was a significant two-way interaction effect ($F_{10,190} = 4.29$; $p <0.001$). Only the Y signal viewed through the Yellow-Green lens produced higher error rates relative to the other conditions.

Results for the deuteranomals are shown in Fig. 7b. The error rates were significantly affected by signal color ($F_{2,28} = 8.31$; $p = 0.001$) and by lens tint ($F_{5,70} = 5.29$; $p < 0.001$), and there was also a significant interaction between signal color and lens tint ($F_{10,140} = 7.18$; $p < 0.001$). The interaction effect reflects the stronger detrimental effect of the Yellow-Green lens for Y signals, such that the Yellow-Green lens resulted in an error rate of 18%, 3.5x higher than that with the Gray lens.

Results for the deuteranopes are shown in Fig. 7c. The error rates were significantly affected by signal color ($F_{2,18} = 16.02$; $p <0.001$) but not lens tint ($F_{5,45} = 1.19$; $p = 0.331$). There was also a significant two-way interaction between the factors ($F_{10,90} = 4.05$, $p < 0.001$) representing a complex series of effects. The error rates for R and Y signals were 21x higher overall than that for G signals, but the pattern of error rates was quite different, with the error rates for R signals exacerbated for the Yellow-Brown and Red-Brown lenses and with the error rates for Y signals exacerbated for the Green and Yellow-Green lenses.

Results for the protanomals are shown in Fig. 7d. The error rates were not significantly affected by either signal color ($F_{2,28}$=2.17; p=0.133) or lens tint ($F_{5,70} = 2.07$ $p = 0.79$), nor was there a significant interaction between signal color and lens tint ($F_{10,140} = 2.403$; $p =0.103$).

Results for the protanopes are shown in Fig. 7e. Error rates were significantly affected by signal color ($F_{2,16} = 4.47$; $p = 0.03$) and lens tint ($F_{5,40} = 3.83$; $p = 0.006$). There was also a significant two-way interaction effect ($F_{10,80} = 4.09$, $p < 0.001$), such that error rates were elevated for the Y signal when viewed through the Yellow-Green lenses.

From considering Figures 7a-e, it is apparent that for most of the color deficient groups there were particular problems for Y signals combined with the Green and Yellow-Green lenses. In addition to this, deuteranopes had particular problems for R signals combined with the Yellow-Brown and Red-Brown lenses. Although the patterns were somewhat different from those seen for response times, in general combinations of signals and sunglasses of similar colors were of particular concern.

DISCUSSION

For the clear lens component of our study, we found that the individuals with a color deficiency had longer response times and made more recognition errors than color normals in response to signals simulating traffic signals.[1] Deutans performed noticeably worse than protans.

In the current paper we considered the effect of different sunglass tints on response times and errors and found that the poorer performance of those with a color deficiency was exacerbated by non-neutral sunglass tints, with combinations of signals and sunglasses of similar colors being of particular concern. Two of these tints (Yellow-Brown and Red-Brown) passed the current European, US and Australian standards, while the Yellow-Green tint failed the Australian standard and the US standard (marginally for the latter), and only the Green tint unequivocally failed all three standards (Table 2).

Anything that limits their ability to design products is generally disliked by the sunglass industry and the restriction placed on them by the color limits of sunglass standards is no exception. It is often pointed out that most analyses, especially those in the detailed papers of Clark, are theoretical. However, given the immense variability of on-road conditions and the range of color vision deficiencies that exist, it is unlikely that adequate on-road studies will ever be funded and the data collected in accident cases have never included documentation of any tinted media worn by the driver(s) involved. So "real-life" studies are not a viable option in exploring the important question of whether sunglass tints compromise the road safety of color deficient individuals; reasonable representations in the laboratory are the only feasible option.

What has been carried out in the current study is an evaluation of tints that are representative of those that are permitted or used in everyday life. The study used contemporary traffic signal design standards in the design of the stimuli and a task that represented the dual task components of driving performance. Therefore the on-road situation was replicated, as best as is possible, in the laboratory.

The study has shown that some sunglass tints, currently permitted for wear by drivers and riders, cause a measurable decrement in the ability of color deficient observers to detect and recognize traffic signals. This is *prima facie* evidence of a risk in the use of these lenses. What this study has not addressed is how that risk might translate into road accidents nor what might be an acceptable risk (since driving is already a risky business), nor how the magnitude of that risk might be considered relative to other avoidable or controllable factors. However, the study has illustrated that the issues that authors such as Clark have raised over many years are real.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Figure 1. Spectral transmittances of sunglasses: a) Clear, Grey and Green; b) Yellow-Green, Yellow-Brown, Red-Brown.

Figure 2. Experimental setup, not to scale.

Figure 3. Chromaticity coordinates of the a) Red, b) Yellow, and c) Red traffic signals without a lens ○ and with the Gray lens □, the Green lens ●, the Yellow-Green lens ▲, the Yellow-Brown lens ∗, and the Red-Brown lens ◆. Coordinates are shown for both the brighter and darker signals. The CIE S 004 limits are marked.

Figure 4. Mean response times of different color vision groups for each sunglass. Error bars represent ±SEM.

Figure 5. Response times of different color vision groups for each of the sunglasses and different signal colors: a) color normals; b) deuteranomals; c) deuteranopes; d) protanomals; e) protanopes. Error bars represent ±SEM.

Figure 6. Error rates of different color vision groups for each sunglass. Error bars represent ±SEM..

Figure 7. Error rates of different color vision groups for each of the sunglasses and different signal colors: a) color normals ; b) deuteranomals ; c) deuteranopes ; d) protanomals ; e) protanopes. Error bars represent ±SEM.

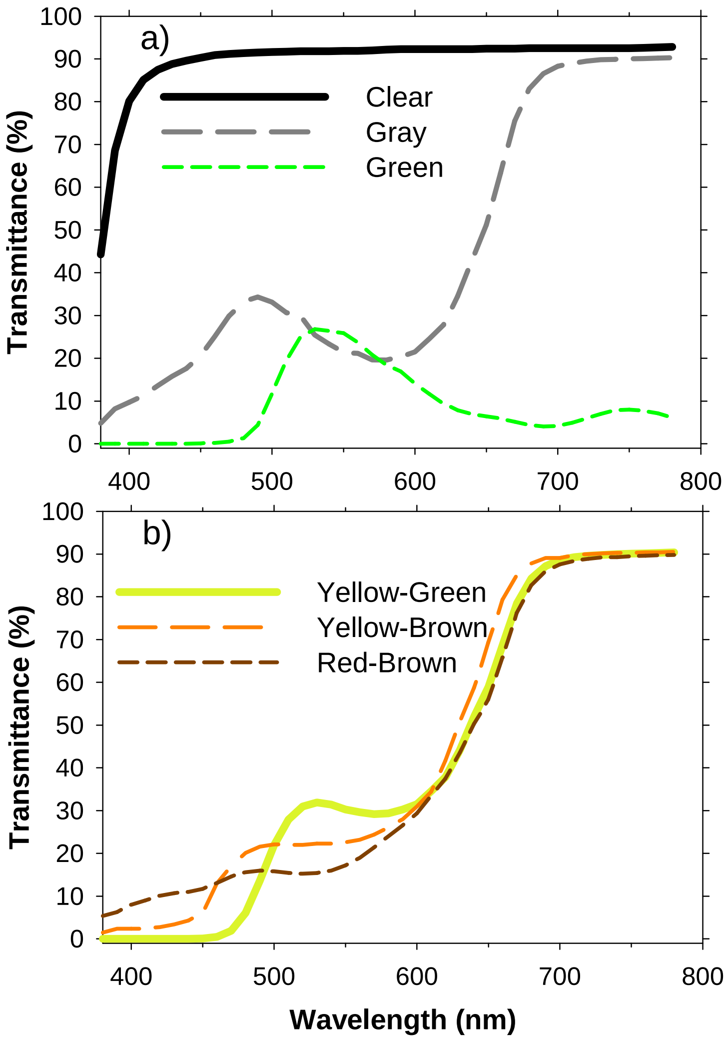
a)
Clear
Gray
Green
b)
Yellow-Green
Yellow-Brown
Red-Brown
Transmittance (%)
Wavelength (nm)
0
10
20
30
40
50
60
70
80
90
100
400
500
600
700
800

Figure 1

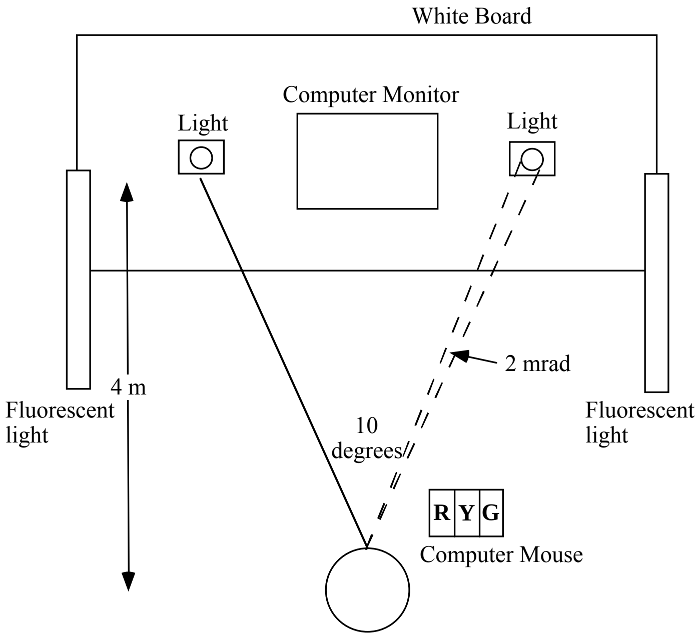
White Board
Computer Monitor
Light
Light
2 mrad
4 m
Fluorescent light
10 degrees
Fluorescent light
R
Y
G
Computer Mouse

Figure 2

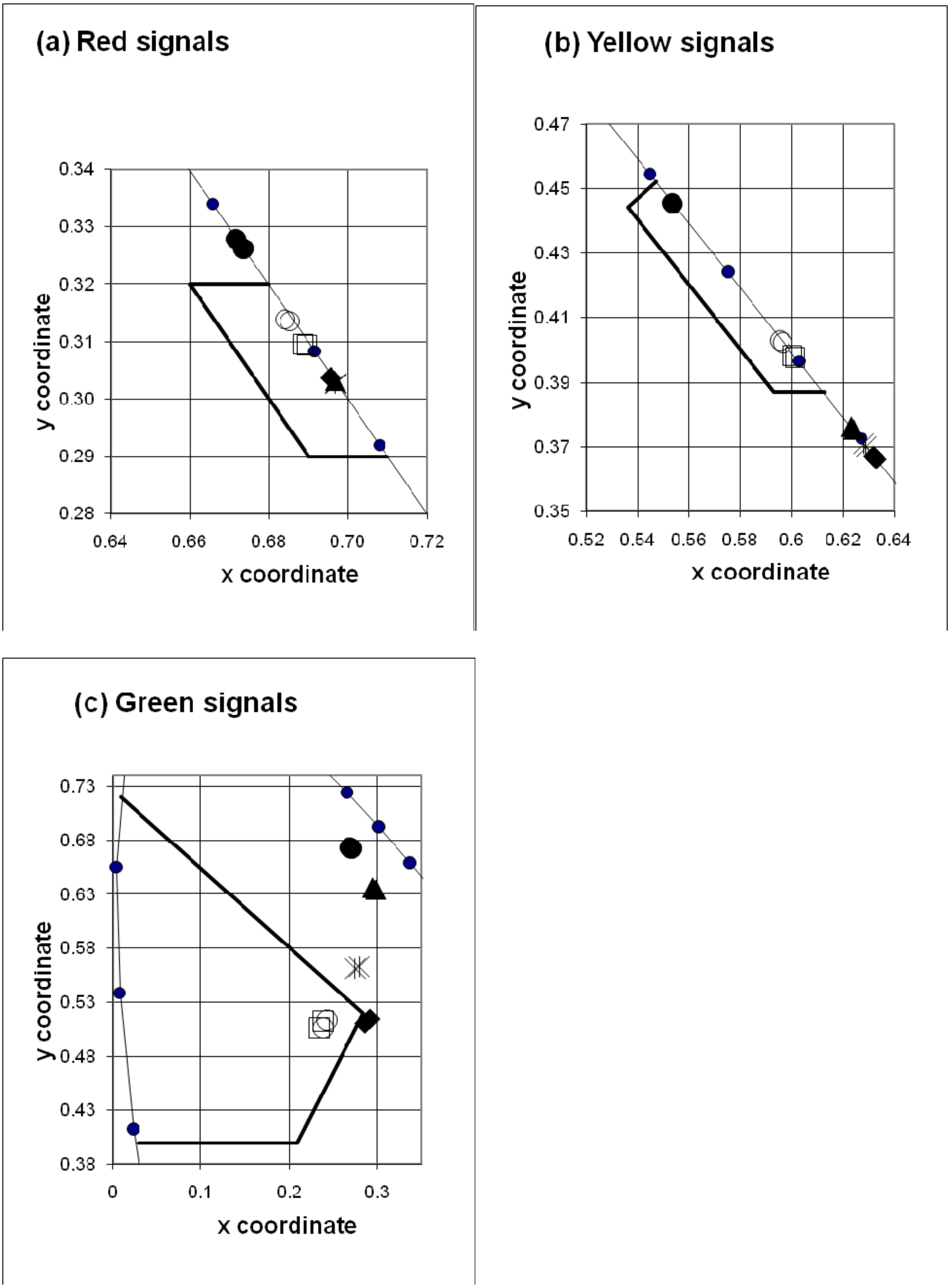
(a) Red signals
y coordinate
x coordinate
0.34
0.33
0.32
0.31
0.30
0.29
0.28
0.64
0.66
0.68
0.70
0.72
(b) Yellow signals
y coordinate
x coordinate
0.47
0.45
0.43
0.41
0.39
0.37
0.35
0.52
0.54
0.56
0.58
0.6
0.62
0.64
(c) Green signals
y coordinate
x coordinate
0.73
0.68
0.63
0.58
0.53
0.48
0.43
0.38
0
0.1
0.2
0.3

Figure 3

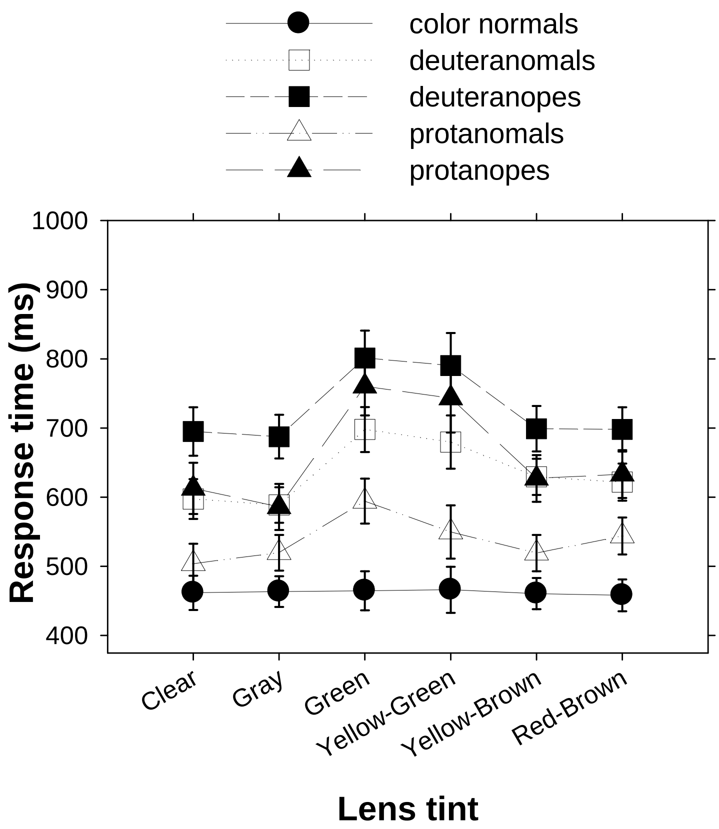
color normals
deuteranomals
deuteranopes
protanomals
protanopes
1000
900
800
700
600
500
400
Response time (ms)
Clear
Gray
Green
Yellow-Green
Yellow-Brown
Red-Brown
Lens tint

Figure 4

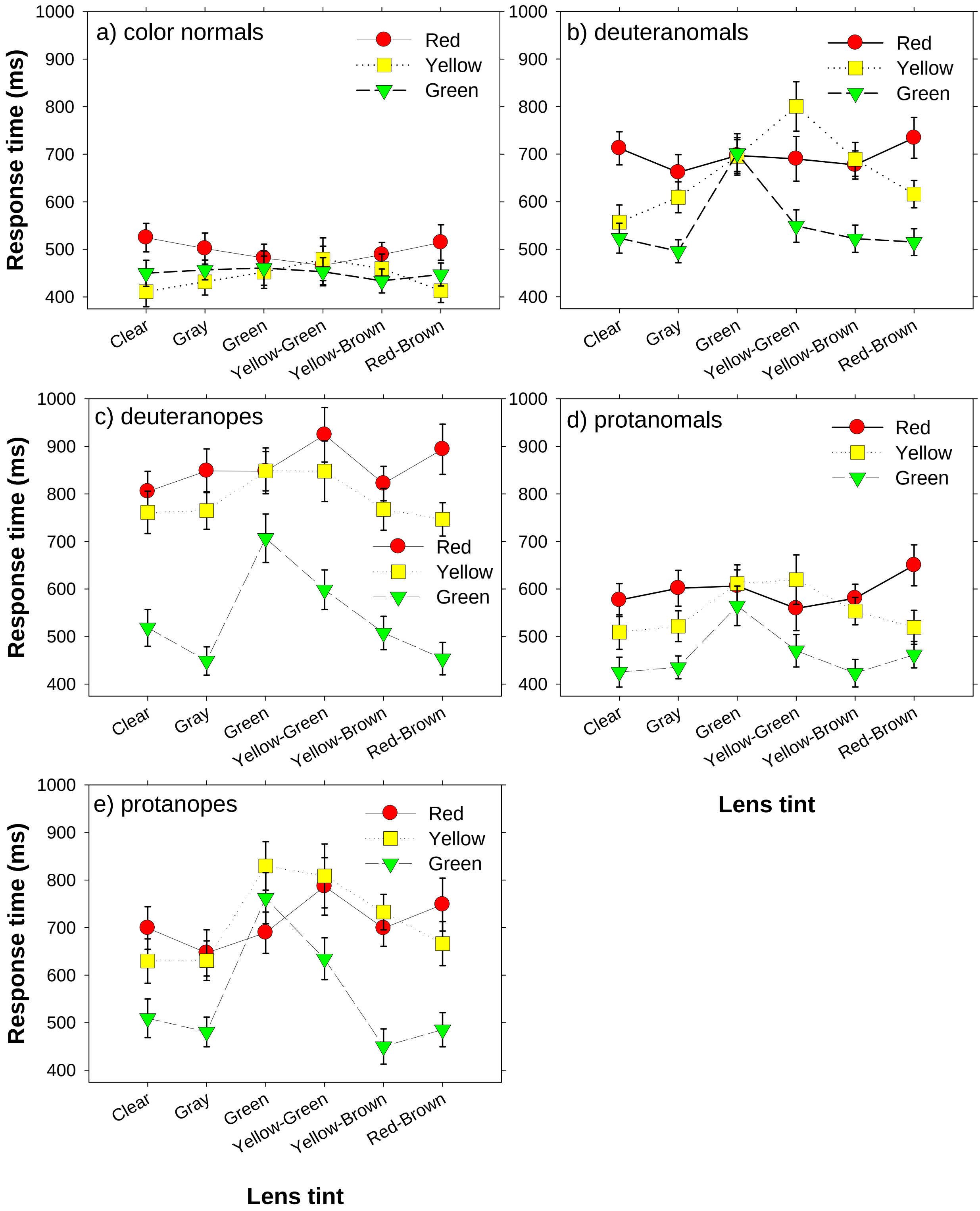
a) color normals
b) deuteranomals
c) deuteranopes
d) protanomals
e) protanopes
Red
Yellow
Green
Response time (ms)
1000
900
800
700
600
500
400
Clear
Gray
Green
Yellow-Green
Yellow-Brown
Red-Brown
Lens tint

Figure 5

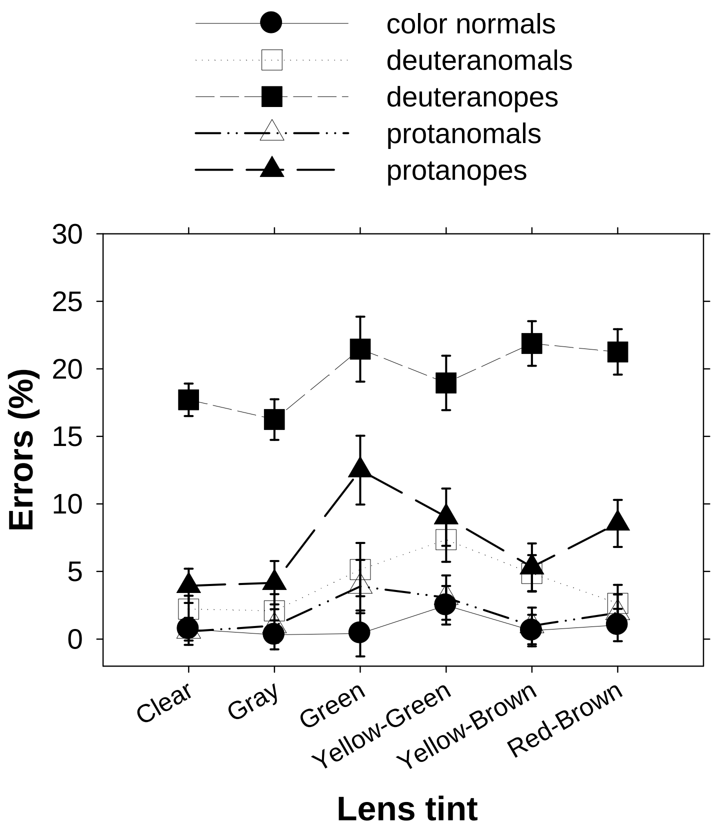
color normals
deuteranomals
deuteranopes
protanomals
protanopes
Errors (%)
30
25
20
15
10
5
0
Clear
Gray
Green
Yellow-Green
Yellow-Brown
Red-Brown
Lens tint

Figure 6

Figure 7

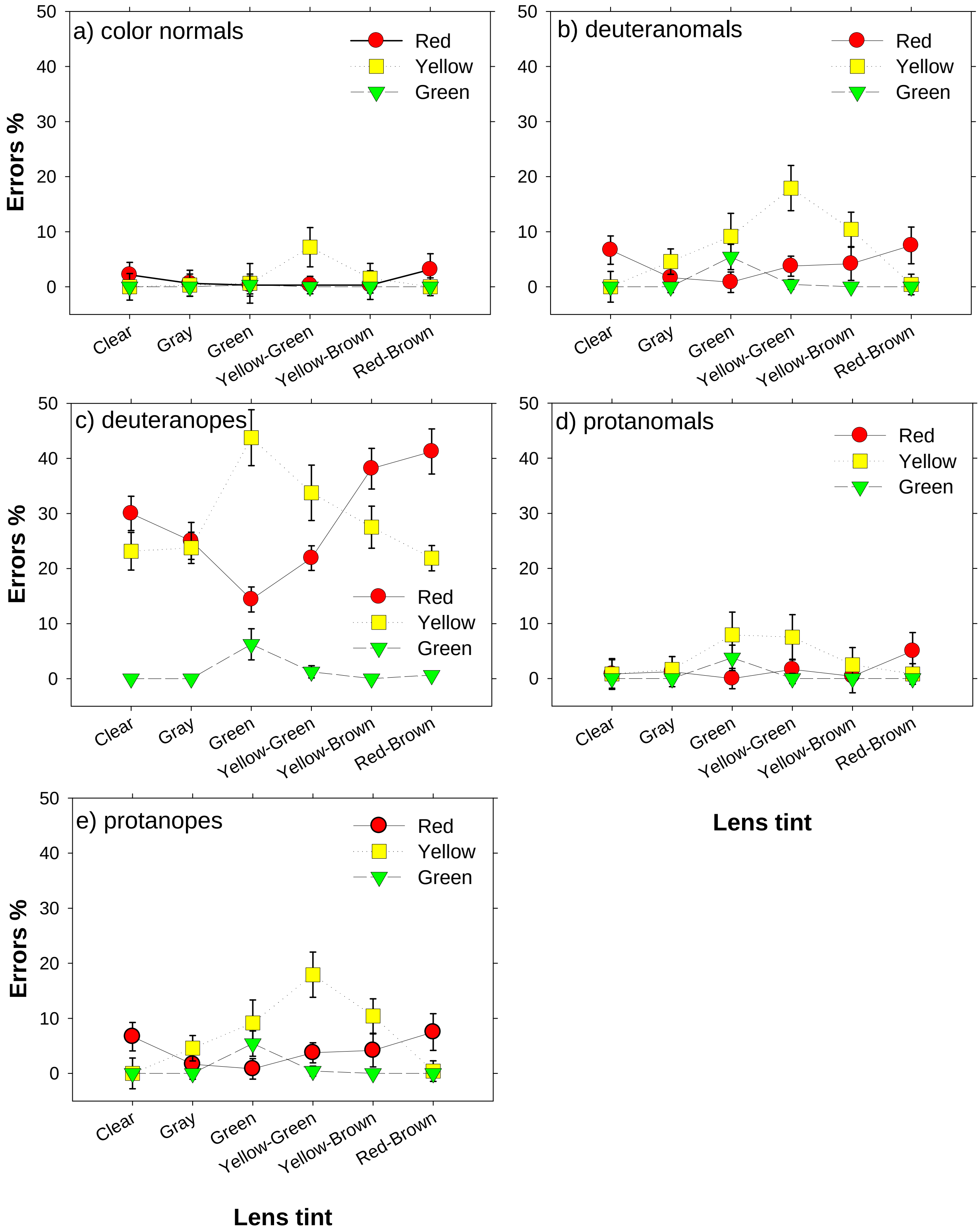
a) color normals
b) deuteranomals
c) deuteranopes
d) protanomals
e) protanopes
Red
Yellow
Green
Errors %
Clear
Gray
Green
Yellow-Green
Yellow-Brown
Red-Brown
Lens tint

Table 1. Requirements limiting coloration in various sunglass standards

The following symbols have been adopted, *viz*

$\tau(\lambda)$ spectral transmittance of the sunglass lens at wavelength λ

$V(\lambda)$ spectral sensitivity of the human eye at wavelength λ

τ_v luminous transmittance of the sunglass lens (varies between CIE Illuminant C τ_c and CIE Standard Illuminant D65 τ_{D65})

$S(\lambda)$ spectral energy distribution of the applicable light source (varies between CIE Illuminant C S_C , CIE Standard Illuminant A S_A and CIE Standard Illuminant D65 S_{D65})[20]

$\tau_\sigma(\lambda)$ spectral transmittance of the traffic signal lens at wavelength λ

$\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ CIE color matching functions[19]

Country/ region	Standard	Coloration factor	Definition	Requirement
Australia	AS 1067-1990 (superseded)[15]	Red signal visibility factor (R)	$\dfrac{\sum_{620}^{780}\tau(\lambda)V(\lambda)S(\lambda)\Delta\lambda}{\tau_v\sum_{620}^{780}V(\lambda)S(\lambda)\Delta\lambda}$	$0.70 \le R \le 1.40$ Otherwise warnings are required Specific purpose type (a) $0.85 \le R \le 1.15$
		Violet factor (V)	$\dfrac{\tau_{420}+\tau_{460}}{2\tau_v}$	$0.3 \le V$ Otherwise warnings are required Specific purpose type (a) $0.5 \le V$
Australia	AS/NZS1067: 2003[18]	Relative visual attenuation quotient for light signal detection (Q)	$\dfrac{\sum_{380}^{780}\tau(\lambda)S_A(\lambda)V(\lambda)\tau_s(\lambda)\Delta\lambda}{\tau_v\sum_{380}^{780}S_A(\lambda)V(\lambda)\tau_s(\lambda)\Delta\lambda}$	$0.80 \le Q_{Red}$ $0.80 \le Q_{Yellow}$ $0.60 \le Q_{Green}$ $0.70 \le Q_{Blue}$ Otherwise warnings are required
		Spectral transmittance		$0.20\tau_v \le \tau_\sigma$ in the region 450-650nm
Europe	EN1836: 2005[17]	As AS/NZS1067: 2003	As AS/NZS1067: 2003	As AS/NZS1067: 2003 except $0.40 \le Q_{Blue}$ rather than $0.70 \le Q_{Blue}$
		Spectral		$0.20\tau_v \le \tau_\sigma$ in the region 500-650nm

		transmittance		Otherwise warnings are required
USA	ANSI Z80.3-2008[16]	Traffic signal transmittance τ_{sig}	$\frac{\sum_{380}^{780} \tau(\lambda) S_A(\lambda) V(\lambda) \tau_s(\lambda) \Delta\lambda}{\sum_{380}^{780} S_A(\lambda) V(\lambda) \tau_s(\lambda) \Delta\lambda}$	$8\% \le \tau_{red}$ $6\% \le \tau_{yellow}$ $6\% \le \tau_{green}$ Note: these are absolute measures, the equivalent measures in AS/NZS1067 and EN1836 are relative to the luminous transmittance.
		Spectral transmittance		$0.20\tau_v \le \tau_\sigma$ in the region 475-650nm Otherwise warnings are required
		Traffic signal chromaticity x, y	x = X/(X+Y+Z) y = Y/(X+Y+Z) z = Z/(X+Y+Z) $X = \sum_{380}^{780} \tau(\lambda) S_A(\lambda) \bar{x}(\lambda) \tau_s(\lambda) \Delta\lambda$ $Y = \sum_{380}^{780} \tau(\lambda) S_A(\lambda) \bar{y}(\lambda) \tau_s(\lambda) \Delta\lambda$ $Z = \sum_{380}^{780} \tau(\lambda) S_A(\lambda) \bar{z}(\lambda) \tau_s(\lambda) \Delta\lambda$	Yellow $0.345 \le y \le 0.565$, $z \le 0.060$ Green region bounded by x, y: 0.038, 0.330 0.205, 0.330 0.345, 0.440 0.313, 0.620 0.080, 0.835 If outside these limits, implicitly not suitable for driving, but no requirement to label as such
		Daylight chromaticity	x = X/(X+Y+Z) y = Y/(X+Y+Z) $X = \sum_{380}^{780} \tau(\lambda) S_{D65}(\lambda) \bar{x}(\lambda) \Delta\lambda$ $Y = \sum_{380}^{780} \tau(\lambda) S_{D65}(\lambda) \bar{y}(\lambda) \Delta\lambda$ $Z = \sum_{380}^{780} \tau(\lambda) S_{D65}(\lambda) \bar{z}(\lambda) \Delta\lambda$	Limit to a region around D65 defined by 29 pairs of x,y. If outside these limits, implicitly not suitable for driving, but no requirement to label as such

Table 2. Coloration characteristics of the tinted lenses as measured by various standards and failures to meet those standards

	(Untinted) Clear	(Neutral) Gray	Green	Yellow -Green	Yellow-Brown	Red-Brown
Luminous transmittance	92%	27%	21%	31%	25%	22%
AS1067-1990						
R factor	1.00	1.10	**0.44**	**1.73** > 1.40	**1.86** > 1.40	**2.10** > 1.40
V factor	1.00	0.8	**0.0** < 0.3	**0.0** < 0.3	**0.2** < 0.3	0.5
AS/NZS1067: 2003						
Q_{Red}	1.00	1.02	**0.56** < 0.80	1.47	1.58	1.82
Q_{Yellow}	1.00	0.99	0.88	1.18	1.21	1.32
Q_{Green}	1.00	1.01	1.13	0.93	0.89	0.79
Q_{Blue}	1.00	1.09	0.80	0.92	1.01	0.97
τ_σ/τ_v	0.99	0.89	**0.01** < 0.20	**0.00** < 0.20	0.24	0.55
EN1836: 2005						
Q_{Red}	1.00	1.00	**0.56** < 0.80	1.47	1.58	1.82
Q_{Yellow}	1.00	0.99	0.88	1.18	1.21	1.32
Q_{Green}	1.00	1.01	1.13	0.93	0.89	0.79
Q_{Blue}	1.00	1.09	0.80	0.92	1.01	0.97
τ_σ/τ_v	1.00	0.90	0.34	0.72	0.90	0.70
ANSI Z80.3-2008						
τ_{red} (%)	92	31	**7.7** < 8.0	48	50	50
τ_{yellow} (%)	92	27	18	49	29	28
Chromaticity yellow	Pass	Pass	Pass	Pass	Pass	Pass
τ_{green} (%)	92	28	22	26	23	28
Chromaticity green	Pass	Pass	**Fail**	Pass	Pass	Pass
Chromaticity daylight	Pass	Pass	**Fail**	**Fail**	Pass	Pass
τ_σ/τ_v	1.00	0.90	**0.04** < 0.20	**0.10** < 0.20	0.75	0.70

Numbers or text in bold indicate a Fail result, with numbers following them indicating the limit that is failed

Table 3: Color vision deficient groups

Type	Selection criteria	Deutan	Protan
Anomalous trichromats	Mild: pass Farnsworth Lantern, pass Farnsworth-Munsell D-15; moderate: fail Farnsworth Lantern, pass Farnsworth-Munsell D-15; strong: fail Farnsworth-Munsell D-15 but not dichromats nor extreme anomalous trichromats[a]	15 (5 of each severity)	15 (5 of each severity)
Dichromats	Match whole red-green range on Nagel anomaloscope even after adaptation on Trendelenberg plate	10	9

The Farnsworth Lantern contains 9 colored light pairs. Colors involved are green, red and white. A pass is two or less identification errors on two runs.

The Farnsworth-Munsell D15 test involves arranging 15 caps in color order: color deficients of sufficient severity make particular types of arrangement errors.

The Nagel anomaloscope requires subjects to match various red-green light mixtures with a yellow light.

[a] Extreme anomalous trichromats were excluded. They are defined on the combined criteria that they accept matches at one extreme of the Nagel anomaloscope range and the normal match and demonstrate range "tuning" after adaptation on the Trendelenberg plate.

REFERENCES

1. Atchison DA, Pedersen CA, Dain SJ, Wood JM. Traffic signal color recognition is a problem for both protan and deutan color-vision deficients. Human Factors 2003;45:495-503.

2. Cole BL, Brown B. Optimum intensity of red road-traffic signal lights for normal and protanopic observers. J Opt Soc Am 1966;56:516-22.

3. Freedman M, Davit PS, Staplin LK, Breton ME. Traffic signal brightness. An examination of nightime dimming. Washington DC: Federal Highway Administration; 1985. (Publication No. FHWA-RD-85-005).

4. Nathan J, Henry GH, Cole BL. Recognition of colored road traffic light signals by normal and color-vision-defective observers. J Opt Soc Am 1964;54:1041-5.

5. Pokorny J, Smith VC, Verriest G, Pinckers AJLG. Congenital and acquired color vision defects. New & York: Grune & Stratton; 1979.

6. Pun HW, Brown B, Lui R. Tinted contact lenses slow reaction time in colour defective observers. Clin Exp Optom 1986;69:213-8.

7. Vingrys AJ, Cole BL. Are colour vision standards justified for the transport industry? Ophthal Physiol Opt 1988;8:257-74.

8. Cole BL. The handicap of abnormal colour vision. Clin Exp Optom 2004;87:258-75.

9. Hager G. Das Sehorgan und das Unfallgeschehen im Strassenverkehr Klin Monatsbl Augenheilkd 1963;142:427-33.

10. Verriest G, Neubauer O, Marre M, Uvijls A. New investigations concerning the relationships between congenital colour vision defects and road traffic security. Int Ophthalmol 1980;2:87-99.

11. Cole BL. Protans and road accidents Clin Exp Optom 2002;85:246-53.

12. Clark BAJ. Color in sunglass lenses. Am J Optom Arch Am Acad Optom 1969;46:825-40.

13. Clark BAJ. Coloration limits for sunglass lenses. Aust J Optom 1970;53:307-15.

14. Australian Standards Association. Australian Standard AS 1067-1971 Sunglasses. 1971.

15. Australian Standards Association. Australian Standard AS 1067-1990 Sunglasses and fashion spectacles. Part 1: Safety requirements. 1990.

16. American National Standards Institute. American national standard requirements for nonprescription sunglasses and fashion eyewear Z80.3 2008.

17. European Standards Organisation. Sunglasses and sunglass filters for general use and filters for direct observation of the sun EN1836:2005.

18. Standards Australia/Standards New Zealand. Australian/New Zealand Standard Sunglasses and fashion spectacles AS/NZS 1067:2003.

19. International Standards Organisation. CIE standard colorimetric observers ISO10527:2007.

20. International Standards Organisation. CIE standard illuminants for colorimetry ISO 10526:2007.

21. Hovis JK, Cranton D, Chou BR. Tinted lenses and the ANSI standards for traffic signal transmittances. Optom Vis Sci 1991;68:750-5.

22. Fisher AJ, Cole BL. The photometric requirements of vehicular traffic signal lanterns. 1974;7:246-65.

23. Standards Australia/Standards New Zealand. Australian/New Zealand Standard Traffic signal lanterns AS/NZS 2144:2002.

24. International Standards Organisation/Commission Internationale de L'Éclairage. Road traffic lights - Photometric properties of 200 mm roundel signals 16508:1999.

25. Commission Internationale de L'Éclairage. Colours of Signal Lights. CIE Standard S 004/E. Vienna: CIE; 2001.